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14. ABSTRACT
We present an analysis of the charging interactivity between surrounding surface materials aboard a spacecraft at geosynchronous altitudes. In particular, bootstrap charging of a small surface may occur if it is surrounded by a large negatively charged surface. Here, a negative potential barrier forms above the small surface, resulting in suppression of photo- and secondary electron emission from that surface. Additionally, the small surface experiences an enhancement of the collection of the photo- and secondary electrons emitted from the surrounding surface. This mechanism results in the charging of the small surface to higher levels than that of the patch in isolation, and in many cases the final potential will reach that of the potential of the larger surrounding surface. With this study we examine bootstrap charging behavior with model data and with data collected on orbit. We have modeled the DSCS-III B7 geosynchronous satellite with realistic geometry and spacecraft materials. Additionally, a previous study has shown that bootstrap charging has been observed on the DSCS-III B7 geosynchronous spacecraft. Bot Astroquartz and Kapton cloth patches charged up to the frame potential of the satellite during periods of severe frame charging. The results of modeling bootstrap charging of a small Kapton patch floating relative to the DSCS-III frame fixed at a potential of 1,000 V show that the patch will indeed charge up negatively to match the frame potential, with the temporal increase in negative potential following an exponential time characteristic.

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Bootstrap Surface Charging at GEO: Modeling and On-Orbit Observations From the DSCS-III B7 Satellite

Linda Habash Krause, David L. Cooke, C. L. Enloe, Gabriel I. Font, Shu T. Lai, M. G. McHarg, and Victor Putz

***Abstract*—We present an analysis of the charging interactivity between surrounding surface materials aboard a spacecraft at geosynchronous altitudes. In particular, bootstrap charging of a small surface may occur if is surrounded by a large negatively charged surface. Here, a negative potential barrier forms above the small surface, resulting in suppression of photo- and secondary electron emission from that surface. Additionally, the small surface experiences an enhancement of the collection of the photo- and secondary electrons emitted from the surrounding surface. This mechanism results in the charging of the small surface to higher levels than that of the patch in isolation, and in many cases the final potential will reach that of the potential of the larger surrounding surface. With this study we examine bootstrap charging behavior with model data and with data collected on orbit. We have modeled the DSCS-III B7 geosynchronous satellite with realistic geometry and spacecraft materials. Additionally, a previous study has shown that bootstrap charging has been observed on the DSCS-III B7 geosynchronous spacecraft. Both Astroquartz and Kapton cloth patches charged up to the frame potential of the satellite during periods of severe frame charging. The results of modeling bootstrap charging of a small Kapton patch floating relative to the DSCS-III frame fixed at a potential of -1,000 V show that the patch will indeed charge up negatively to match the frame potential, with the temporal increase in negative potential following an exponential time characteristic.**

***Index Terms*—Bootstrap charging, Defense Satellite Communication System (DSCS-III), differential charging, GEO satellite charging, spacecraft surface charging.**

I. Introduction

SATELLITES in geosynchronous earth orbit (GEO) are regularly exposed to a variable space environment, primarily consisting of low energy plasma particles (with $E \sim 100$ eV), solar ionizing radiation (e.g., extreme ultraviolet radiation), and occasionally the so-called surface "charging electrons"; that is, those with energies on the order of 10 keV to 50 keV. Fluxes of charging electrons at GEO tend to drastically increase during periods of geomagnetic activity, especially with the injection of hot plasma into the ring current. Under such circumstances, the GEO satellite may experience frame charging relative to the surrounding plasma potential. The frame potential ϕ is calculated analytically using the Langmuir orbit-limited current balance equation [1]:

$$I_i(\phi) - I_e(\phi) = I_i(0)\left(1 - \frac{q_i\phi}{kT_i}\right) - I_e(0)\exp\left(-\frac{q_e\phi}{kT_e}\right) = 0$$

where q_i, q_e, T_i, and T_e are the ion and electron charges and the ion and electron temperatures, respectively. If secondary, backscattered, or photo- electrons are ejected from the spacecraft in sufficient quantities to contribute significantly to the current balance, their inclusion in the form of a positive current must be included in the above equation. Indeed, several studies have shown that both secondary and photo-electron current play a significant role in the charging behavior of a GEO spacecraft and must be included in charging computations. In general, these secondary and photo-electrons tend to reduce the severity of negative surface charging at GEO. But what happens if something prevents these secondary and photo-electrons from leaving the near-spacecraft environment? With these secondary and photo-electrons removed from the current balance process, the surfaces tend to charge up to higher negative potentials than surfaces where these electrons were able to escape. This charging enhancement is called bootstrap charging. It is especially prevalent among small surfaces insulated from and surrounded by larger surfaces. In this case, if the larger surface is charged to a significant negative potential, a saddle point in the potential field can develop directly over the smaller surface, resulting in a potential barrier that reflects secondary and photo-electrons back to the smaller surface. Additionally, secondary and photo-electrons ejected from adjacent surfaces could be channeled by the potential structure to strike the smaller surface, again resulting in an enhancement of negative charging of the small patch. Evidence of the bootstrap charging process has been found in both modeling [2] and on-orbit data [3], but this paper will provide a detailed comparison between the two by focusing on modeling and observations of bootstrap charging as seen for a particular satellite: the Defense Satellite Communication System (DSCS-III).

With their seminal work in the area of bootstrap charging, Mandell *et al.* [4] demonstrated that multidimensional effects must be taken into consideration to accurately model the surface potential of an object in a GEO plasma environment. They modeled a test satellite in the form of a tessellated sphere, comprised of 26 facets, which consisted of a Teflon coating over

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a conductive substrate. The study simulated the immersion of this sphere in a storm-time environment of a 20 keV plasma. It was found that even when the satellite is illuminated by sunlight, it was still able to charge to large negative potentials due to electric fields that were generated external to the spacecraft which could only be generated with a multi-dimensional model. More precisely, when multidimensional effects were incorporated into the model, potential structures in the regions surrounding the spacecraft developed in response to accumulated negative charge on the shaded side of the spacecraft—which resulted in a saddle point in the potential contours at a variable stand-off above the sunlit surface. This saddle point was responsible for blocking the relatively low-energy photo-electrons from escaping the sunlit surface since it was positive relative to the saddle point potential. Furthermore, it was shown that the sunlit and shaded surfaces were connected electrically through the spacecraft ground with connections that could be represented via an equivalent circuit with parallel resistance and capacitance at each junction. Finally, the authors concluded that a dielectric patch, when charged to very high levels relative to the spacecraft frame, can have "an influence out of proportion to its area," precisely due to the barrier effect on particle trajectories in the vicinity of the spacecraft. This point will be of key importance to the work in the present study.

The Defense Satellite Communication System (DSCS-III) is comprised of 10 satellites located in geosynchronous orbit. One satellite in particular, DSCS-III B7, was instrumented with sophisticated plasma and satellite surface charging sensors, along with an autonomous charge neutralization source, that formed an experimental package meant to investigate the relationship between the plasma environment and various forms of surface charging behavior. Previous studies have shown that the DSCS satellite would experience sunlit frame charging on the order of hundreds of volts negative during periods of storm-time injection of charging electrons in the GEO environment, and would experience frame charging of thousands of volts negative during eclipse periods (when the satellite would pass through the Earth's shadow.) Differential charging of two dielectric patches, Kapton and Astroquartz, was observed regularly on the order of thousands of volts negative relative to the spacecraft frame when the patches were shaded. Lai *et al.* [3] studied a particular differential charging event in which the authors argued that bootstrap charging of the patch was observed. It is this observation which motivated this study.

The present work is organized as follows. Section II describes the modeling procedure by which DSCS-III bootstrap charging is computed. Charging behavior is examined in detail for the effects of sunlight exposure on the non-metalicized RF-transparent antenna shrouds, and these computations appear in Section III. An attempt is made to replicate the event of bootstrap charging as seen in the DSCS-III data by Lai *et al.* [3], with results and discussion appearing in Section IV. The paper concludes with a summary of findings in Section V.

II. DSCS-III Modeling in NASCAP-2K

The NASA Spacecraft Charging Analysis Program (NASCAP) has been used for modeling satellite surface charging since the mid-70s. NASCAP-2K is the latest major release of the code, which calculates currents and potentials on facets of a three-dimensional surface model immersed in a simulated space plasma environment representative of the near-earth space plasma environment. Throughout the more than 30 years of development, NASCAP-2K has evolved into a sophisticated suite of physics-based models capable of particle tracking, modeling sheath and wake structures, incorporation of Particle-In-Cell (PIC) calculations, specification of user-defined nested grids, and a variety of options for the addition of processes for those who are willing to write their own code. With its native modeler, investigators can build their own spacecraft with realistic three-dimensional geometries and materials that incorporate properties from laboratory testing on typical spacecraft materials, including Teflon, aluminized Kapton, multi-layer insulation thermal blankets, etc. In a recent publication, *Mandell et al.* [2] demonstrated the efficacy of using NASCAP-2K to model the charging of the Mercury-bound MESSENGER satellite in an interplanetary environment. With this model, they demonstrated that because of the differential charging of various surfaces on the satellite, low energy ($E < 50$ eV) ions may experience significant perturbations in their motion in the vicinity of the spacecraft, resulting in a significant chance for error in their measurements. Because NASCAP-2K has a solid heritage of proven capability to calculate spacecraft charging behavior of complex surface configurations, it was the modeling package of choice for the present study.

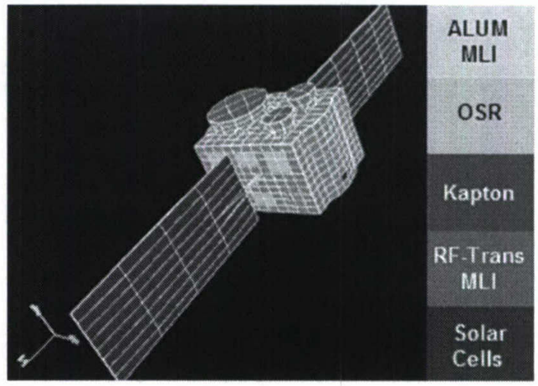

Fig. 1. Model of DSCS-III in NASCAP-2K.

The basic geometry of DSCS has been modeled using NASCAP-2K's Object Tool Kit, and an isometric view of the model appears in Fig. 1. The majority of the satellite is covered with Multi-Layer Insulation (MLI) thermal blankets that have been aluminized on the outer surface to provide a more effective electrical connection (i.e., one of lower electrical resistivity) to the space plasma environment. The shroud coverings over the satellite antennas are RF transparent, and so it is presumed that there is no aluminization of these MLI blankets. Optical solar reflectors (OSRs) are included on the sides of the spacecraft, as well as solar panels attached to the spacecraft via aluminum booms. The solar panels extend approximately 11.62 m from tip to tip, and the bounding box of the DSCS body has the dimensions $2.38 \text{ m} \times 1.93 \text{ m} \times 1.86 \text{ m}$. A small Kapton patch, which represents the Kapton of the differential charging

TABLE I
INITIAL STORM TIME ENVIRONMENTAL PLASMA PARAMETERS USED IN NASCAP SIMULATIONS

Parameter	Value
Electron Density (m^{-3})	8.0×10^5
Electron Temperature (eV)	1.2×10^4
Ion Density (m^{-3})	2.4×10^5
Ion Temperature (eV)	3.0×10^4

sensor onboard the DSCS-III B7 satellite, is placed on the DSCS body. Surface materials were characterized by a set of properties found in the NASA Space Environmental Effects Materials Handbook, and these properties include material thickness, dielectric constant, average atomic number, bulk and surface conductivities, photo-emission yield, proton yield, and a complex function for the description of secondary electron yield.

The basic set of plasma parameters used to characterize the environment for this study is based on the NASA Worst Case charging environment with the modification of one parameter: the electron density. The plasma is thus assumed to be a one-temperature Maxwellian, and the storm time environment is given parameters given in Table I. For the static environment simulations, two sun-vector conditions were tested: one with the sun vector illuminating the antenna shroud at shallow angle, and the other with shaded antenna shrouds. In this manner, it was possible to test for the effects of a strongly charged non-metalicized dielectric surface on the frame potential of the primary DSCS structure. Additionally, to investigate the behavior of charging at the cross-over point going from sunlight to eclipse charging, we simulated an environment in which the satellite illumination was turned off half-way through the simulation. The typical length of simulated time on orbit for a static environment was 300 seconds, and for simulating an eclipse crossing, the total duration of simulated time was 600 seconds, with illumination turned off at $t = 300$ seconds after the start of the simulation.

III. DSCS-III MODELING RESULTS

First we examine the charging behavior of the DSCS satellite when immersed in a storm-time plasma with sunlit antenna shrouds. The angle of incidence of sunlight on the antenna shrouds is purposely shallow to demonstrate the importance of photo-emission from those surfaces in the control of the entire spacecraft potential. The sun vector is incident on and almost normal to the surfaces of the solar panels. The simulation was run for 300 seconds of exposure to this storm-time plasma at GEO, and the resulting surface charging is presented in Fig. 2. The primary frame of DSCS-III charges up negatively to -420 V, which is a reasonable charging level for the environmental conditions simulated here. The OSRs have a slightly more positive charging level, which is expected due to the large secondary electron emissivity characteristic of the material. The antenna shrouds are also of lower negative potential, but this is due to the high photo-electron emissivity of the materials. Finally, the solar panels are non-uniformly charged, with more severe negative charging on the inner edges closer to the spacecraft body than the outer edges of the panels. The most positive potential of the spacecraft is -160 V at the tips of the solar panels.

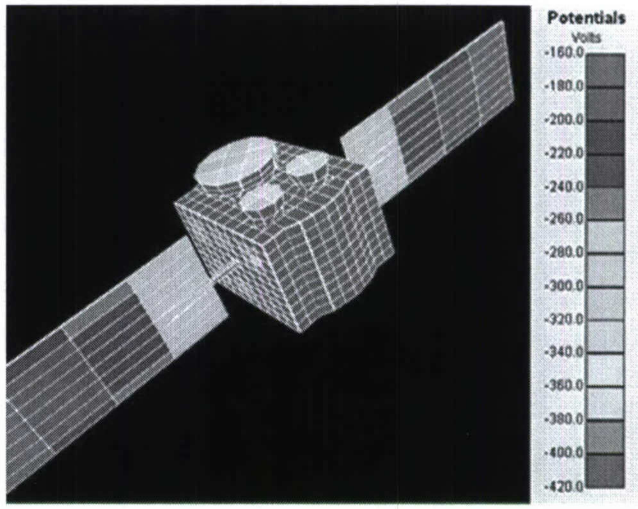

Fig. 2. Surface charging of DSCS-III when exposed to a storm-time GEO plasma environment. Here, the RF-transparent (non-metalicized) antenna shrouds are sunlit with grazing incidence sun vector incident on the shroud.

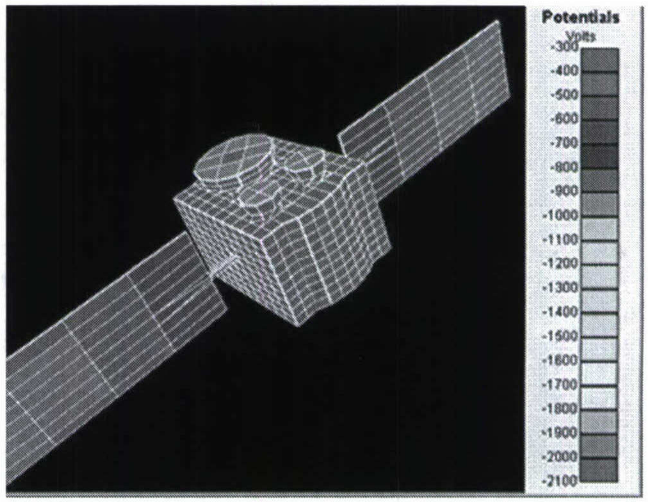

Fig. 3. DSCS-III Surface Potential after 300 seconds exposed to storm-time plasma. Antenna shrouds are shaded in this case.

Similar computations were run for the case where the DSCS satellite was exposed to the same plasma environment, but the sun angle was changed slightly so that the shrouds were shaded. The solar panels were still illuminated with almost-normal incidence of the sun vector. Charging results appear in Fig. 3. Now the frame potential is -900 V, almost a 500 V difference from the case where the shrouds were illuminated by sunlight. The OSRs have the same potential as the DSCS frame, and the solar panels also charge up to much higher potentials than the case for sunlit shrouds, with a -700 V inner edge potential in the shaded shroud case compared to the -300 V inner edge potential for the sunlit shroud case. The shrouds themselves exhibited the strongest negative charging, with the center of the largest shroud reaching -2100 V.

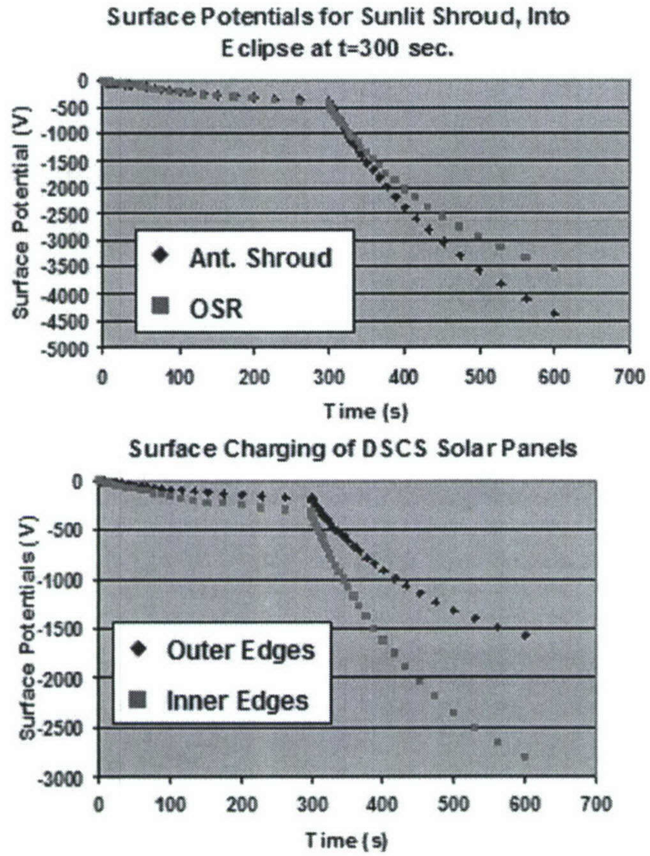

Fig. 4. Time series of DSCS-III Surface Potential while exposed to storm-time plasma. Satellite is sunlit until t = 300 sec, at which time it enters into the Earth's shadow. Antenna Shroud and solar reflectors are represented in the top-most figure, whereas solar panels are represented on the bottom.

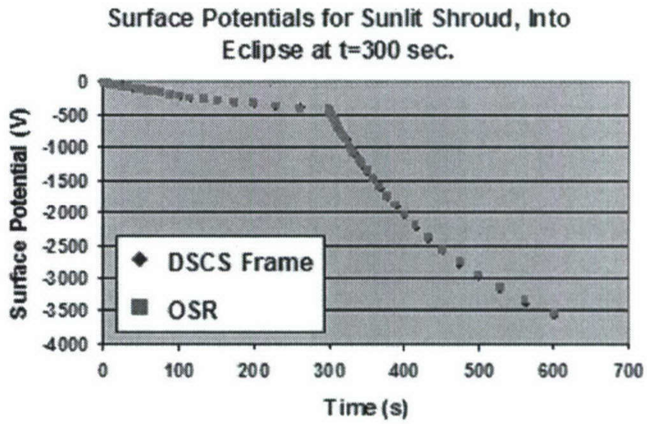

Fig. 5. Time series of DSCS-III Surface Frame Potential while exposed to storm-time plasma, as compared to the surface charging of the Optical Solar Reflectors (OSRs). Satellite is sunlit until t = 300 sec, at which time it enters into the Earth's shadow. Antenna Shroud is initially sunlit.

Next, we perform computations of the charging behavior of the DSCS satellite passing from a sunlit storm-time plasma environment into the shadow of the Earth. For satellites at GEO, these eclipse crossings occur only for a relatively short fraction of the number of orbits, and when they do occur, they do not last for very long, with a maximum duration close to an hour. Here, we only model the transition into the eclipse, with sunlight in the initial half of the simulation, and zero illumination in the second half of the simulation. The entire simulation is run for 600 seconds, and the time series of the charging of the individual components for the case of grazing incidence of sunlight on the shroud appear in Fig. 4. The potentials in Fig. 4 represent the minimum potentials achieved over all surfaces of the antenna shrouds and the OSRs. The charging behavior is similar for both the OSR and the shrouds when the spacecraft is illuminated by sunlight, but the charging curves diverge when the satellite passes into eclipse. This is because of the relative importance of photo-electron emission versus secondary electron emission for the two materials: photo-emissivity plays a dominant role in the current balance to the shroud, and when this source is removed, it tends to charge up more severely than the OSRs, whose high secondary yield is not (directly) affected by the removal of sunlight. When considering the purpose of an OSR, this makes sense: OSRs reflect a lot of the solar illumination, and when photons are optically reflected from a material, they do not participate in the ejection of photoelectrons. Thus, removal of sunlight from such a material would not directly influence the contribution of net positive current to the material, and thus the charging levels. The fact that the OSRs are charged up more negatively in eclipse than in sunlight is an indication that bootstrap charging due to a more negative spacecraft frame may be functioning to prevent secondary electron from escaping the region of the OSRs. In fact, observing the time series for the frame and OSR charging in Fig. 5, we see that the OSRs track the body potential almost precisely throughout the simulation, with the exception of the OSRs being slightly more positive during the times of severe charging in eclipse.

Finally, we present results for the case of an eclipse crossing with the same environmental parameters as in the previous case, but with one exception: the antenna shroud is initially shaded. Results appear in Fig. 6. For all components, including the OSRs, the solar panels, and the antenna shroud, the final charging levels after 600 seconds of simulation time are more strongly negative than the corresponding charging levels for the case of the eclipse crossing with an initially sunlit antenna shroud. Additionally, though not shown graphically here, the OSR and frame potentials again track each other precisely, as in the case with the initially sunlit shroud.

IV. DSCS-III Bootstrap Charging: Observations and Modeling

A detailed review of the DSCS plasma instrumentation used to characterize surface charging and the plasma environment appear in several papers, and we only present a brief overview of the observations here. Differential charging data were accumulated for two dielectric materials common to spacecraft: Astroquartz fabric and Kapton film. Each of these materials was placed over a Surface Potential Monitor (SPM), which provided the voltage between the material and the spacecraft frame. The DSCS-III frame-to-plasma potential was determined using so-called ion peak method. Ion spectra are used to infer the frame potential relative to the background plasma by relating the peak in the ion spectrum (at any given time) to the accelerating voltage through which the ambient ions gain energy. Extensive

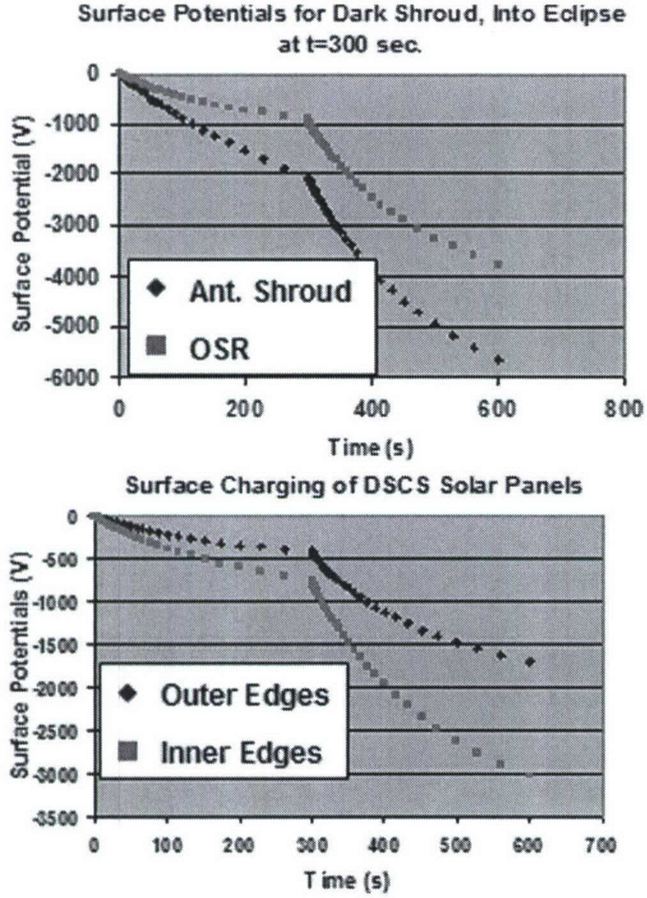

Fig. 6. Time series of DSCS-III Surface Potential while exposed to storm-time plasma. Antenna Shroud and solar reflectors are represented in the top-most figure, whereas solar panels are represented on the bottom.

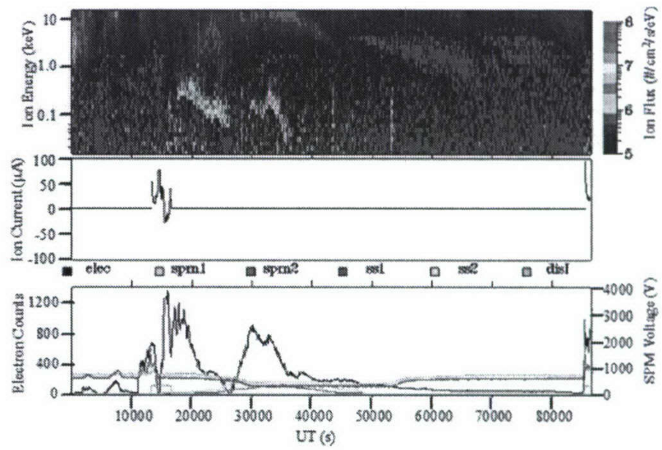

Fig. 7. DSCS III B-7 surface charging and particle observations appear over a 24 hour period, beginning at midnight UT (20:30 MLT); data for 29 August 1996 are shown here.

reviews of both frame and differential charging events observed on DSCS-III appear in [5] and [6], respectively. A typical set of data illustrating spacecraft charging and particle fluxes appears in Fig. 7. The data are for day 242 of 1996, starting from midnight Universal Time (UT) and lasting for one complete 24 hour orbit. Ion spectra, differential in energy, appear in the top panel. The middle panel is a relative measure of plasma current escaping the Xe plasma contactor. There are several traces overlaid in the bottom panel: a) the white trace represents the electron count integrated over the energy range from 20 keV to 50 keV; b) the green trace represents the SPM 1 (Astroquartz) voltage; c) the red trace represents the SPM 2 (Kapton) voltage; d) the blue represents the SPM 1 sun sensor; e) the cyan trace represents the SPM 2 sun sensor, and f) the orange trace represents the on/off state of the Xe plasma contactor.

A particular set of DSCS observations has been postulated to be an indication of bootstrap charging of one of the differential charging sensors aboard the spacecraft. The data in question appear in Fig. 8. Here, we see that the Astroquartz potential is variable in intensity above 2,000 V until the satellite passes into eclipse, with the region annotated by the "FRAME CHARGING" label on the figure. At that point, the frame potential sharply increases in negative potential to a value of approximately $-3{,}000$ V, as evidenced by the peak in the ion spectra at that energy in the spectrogram. At that same point in time at the eclipse entry point, both the Kapton and Astroquartz potentials drop down to their background (zero-charged) states. Lai *et al.* [3] contend this is evidence of bootstrap charging aboard DSCS. The potentials of both materials decay with an exponential, which is consistent with the RC-equivalent circuit model discussed in the introduction of this paper. The rationale is that the charged surfaces of the dielectrics were at a more negative potential than the surrounding spacecraft frame, and therefore bootstrap charging caused the dielectrics to become more negative until their potentials matched that of the spacecraft—resulting in a relative value of dielectric-to-frame differential charging of zero.

We have attempted to model this effect with NASCAP-2K. With our simulations set up to compute the charging behavior of a Kapton patch on the body of the DSCS satellite as it passes from sunlight exposure into eclipse, as described in Section II, we compute the time series of both the frame and Kapton patch potential, with results appearing in Fig. 9. The patch and satellite body potentials track each other closely up until the satellite enters eclipse, at which point the patch charges up to stronger negative potentials than the DSCS body. This would indicate that perhaps there was bootstrap charging of the Kapton patch that occurred during sunlight exposure, but because the satellite body was relatively more positive in eclipse, conditions for bootstrap charging were not present for this particular case. Next, we modeled the spacecraft body as having a fixed potential at -1000 V, and then calculated the potential of a sunlit Kapton patch, with results appearing on a semi-log scale (on the time axis) in Fig. 10. Here, we see that the Kapton patch clearly increases in negative potential rapidly over time with an exponential relationship, as evidenced by the linear relationship between potential and the common log of the time in the first two to three seconds of the simulation.

We can conclude from this modeling effort that, though the conditions which produced a satellite body which was more strongly charged negatively relative to a dielectric patch were not reproduced with this simulation, indeed when the somewhat

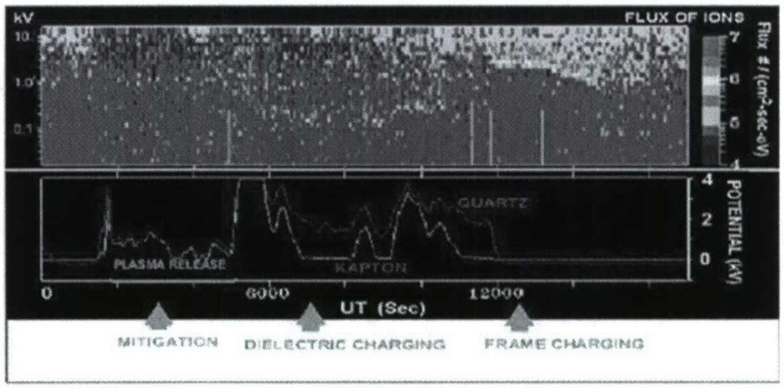

Fig. 8. DSCS III B-7 surface charging data from *Lai et al., 2001*. The steep increase in frame charging coincides with satellite passing into eclipse. Differential charging of quartz patch drops to zero.

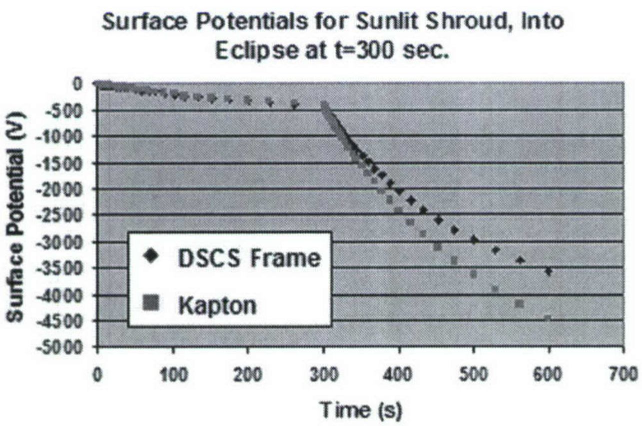

Fig. 9. Model results of DSCS III B-7 surface charging behavior during passage into eclipse. For Kapton patch on a conductor isolated from the spacecraft frame, both charge up severely negatively upon entering earth's shadow.

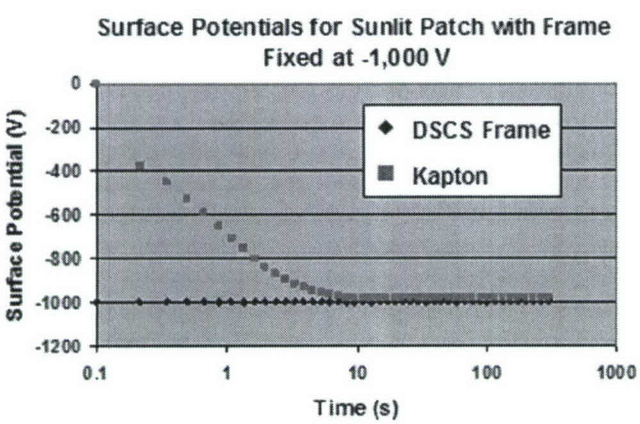

Fig. 10. Surface potentials of the Kapton patch are plotted as a function of time and compared with the fixed DSCS frame potential of -1000 V. The Kapton patch experiences an exponential increase in negative potential until the potential is almost that of the satellite frame.

artificial case of fixing a satellite body potential at a large negative value, even sunlit dielectrics will charge up negatively with an exponential time characteristic indicative of an RC equivalent circuit. This result is consistent with the fact that differential charging was not observed in sunlight. Any negative charging of the spacecraft body must be matched by corresponding charging of the dielectric surfaces on the differential charging sensors, which would explain why no events of differential charging of the sunlit Surface Potential Monitors were observed after an exhaustive survey of the 5.5 years of DSCS differential charging data [6].

V. Summary of Findings

We have developed a model of the DSCS-III satellite, complete with aluminized MLI blankets on the body and back faces of the solar panels, solar cells on the front surface of the solar panels, Optical Solar Reflectors on the body of the satellite, and a single Kapton patch on the body of the satellite. With the modeling results from our NASCAP-2K simulations, we have found that the RF-transparent non-metalicized antenna shrouds will play a dominant role in the control of the spacecraft frame potential, with sunlit shrouds resulting in a significantly lower frame potentials than shaded shrouds for simulations in otherwise similar environments. Additionally, when the satellite is modeled in the Earth's shadow, the frame potential increases rapidly as it enters eclipse, which is consistent with charging behavior seen in DSCS-III observations. Attempts to model the DSCS-III observations which are postulated to be evidence of bootstrap charging of small dielectric patches were partially successful in that a negatively charged body did indeed prompt negative charging of a small Kapton patch to match the body potential. Further research must be performed to determine how to model the environmental conditions which are necessary to produce a spacecraft body which is charged to much higher negative potentials than a dielectric patch, thus setting up the initial conditions for modeling bootstrap charging in a realistic plasma environment.

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